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Global Food Security (Food Sovereignty Movements), Bioterrorism & A.I: Opportunities and Challenges for Global Food Regulatory Systems.

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ABSTRACT: Food sovereignty and global food security are facing increasing pressure from population growth, climate change, geopolitical conflicts, environmental degradation, pandemics and disruptions in international trade. The interconnectedness across global markets and it is creating vulnerability that might impact the accessibility, food availability, utilisation, and stability of food resources. Bioterrorism and agroterrorism are presenting additional threats as there is deliberate contamination of livestock, crops and food and it is creating public health issues and having economic and trade consequences. The implication of the review is to examine the relationship between food sovereignty, food security, biological threats and emerging use of AI, digital technology and robotics in the food regulatory system. The review is going to address how the traditional CARVER+Shock Vulnerability-assessment approach and AI, Machine learning, IoT and big-data analytics are going to support contamination detection, predictive analytics, automated inspection, disease surveillance and end-to-end traceability required in food regulation. The review is going to draw understanding from Covid-19, in particular the relationship to transportation, trade, cultural labour, certification and inspection and how this caused the introduction of the need for technology-resilient governance. The synthesis of the research study showed that digital technologies have the capacity to shift food regulation from dominantly reactive approaches to more continuous, preventive, proactive and predictive approaches. However, implementation of digital technologies is mostly constrained by investment and infrastructure gaps that are followed by cybersecurity and privacy risks, data quality risks, ethical oversight, algorithmic bias, limited technological capacity and inconsistency with international standards. The review has emphasised that there are required means of integration capacity, building international collaboration, ethical oversight, integrated governance, public-private partnership and equitable access for digital infrastructure to strengthen food sovereignty, global food security and food defence.

1. INTRODUCTION

Food security and food sovereignty have become central concerns in global development, public health, and agricultural policy in the 21st century. Food and Agriculture Organisation (FAO) defines food security as when all people, at all times, have

physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Food sovereignty extends this concept by emphasising the rights of communities and nations to define their own food systems, prioritise local agricultural production, protect natural resources, and ensure culturally appropriate food for their populations [5].

In recent decades, rapid globalisation, urbanisation, climate change, population growth, and technological advancements have significantly transformed food production and distribution networks. While globalisation has improved food availability and international trade, it has increased dependence on complex supply chains that are vulnerable to disruptions [5]. Events such as extreme weather conditions, geopolitical conflicts, pandemics, economic crises, and biological threats have demonstrated the fragility of global food systems. The COVID-19 pandemic, for example, disrupted agricultural production, transportation, labour availability, and international trade, exposing weaknesses in food supply chains [14].

Bioterrorism has gained increasing attention from policymakers, researchers, and international organisations. Bioterrorism refers to the deliberate release of biological agents, including pathogens, toxins, or harmful microorganisms, with the intention of causing disease, economic damage, social disruption, or public panic [22]. Agricultural bioterrorism, known as agroterrorism, specifically targets crops, livestock, and food processing facilities. Such attacks can have devastating consequences, including food shortages, loss of consumer confidence, trade restrictions, environmental degradation, and significant economic losses [23].

To overcome these issues, governments and regulatory agencies have adopted various food defence and risk assessment frameworks. One widely recognised approach is the CARVER+Shock model, which evaluates vulnerabilities in food systems based on criticality, accessibility, recuperability, vulnerability, effect, recognizability, and shock value[6]. Although these frameworks have improved preparedness and vulnerability assessment, they often rely on periodic evaluations and may not provide the real-time monitoring and predictive capabilities needed to respond effectively to emerging threats in dynamic food environments [7].

Advances in Artificial Intelligence (AI), machine learning, robotics, blockchain technology, Internet of Things (IoT), and big data analytics are creating unprecedented opportunities to strengthen food regulatory systems and enhance global food security [11]. Robotics and automated inspection systems are increasingly being used in food processing and quality control, reducing human error and increasing efficiency [13]. Similarly, blockchain-based traceability systems provide transparent and tamper-resistant records that improve accountability and consumer confidence throughout food supply chains [20].

The integration of AI and digital technologies into food safety and regulatory systems has the potential to transform traditional reactive approaches into proactive and predictive frameworks [12]. Real-time surveillance, intelligent risk assessment, automated detection of contaminants, and rapid response mechanisms can significantly improve the resilience of food systems against both accidental and intentional threats. Furthermore, AI-supported early warning systems can assist policymakers and regulatory agencies in anticipating disruptions before they escalate into large-scale crises [18].

Despite these promising developments, several challenges remain. High implementation costs, limited technological infrastructure, data privacy concerns, cybersecurity risks, algorithmic bias, and the lack of harmonised international standards continue to hinder the widespread adoption of AI-based food governance systems, particularly in developing countries [11]. Addressing these challenges requires coordinated efforts among governments, international organisations, industry stakeholders, researchers, and technology developers to ensure that digital innovations are accessible, ethical, and effective [13].

This review critically examines the intersection of food sovereignty, food security, bioterrorism, and emerging AI technologies within the context of global food regulatory systems. It explores the threats posed by biological attacks on food and agricultural sectors, evaluates current food defence frameworks, analyses the role of AI and robotics in enhancing food safety and resilience, and discusses policy recommendations for building future-ready food governance systems.

Global Food Sovereignty



Figure 1: conceptual framework of global food sovereignty

2. LITERATURE REVIEW

Food security is a multidimensional concept that encompasses the availability, accessibility, utilisation, and stability of food resources. The Food and Agriculture Organisation (FAO) defines food security as a condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life [5]. Over the past few decades, food security has become a central concern for governments, international organisations, and policymakers due to the increasing pressures of population growth, climate change, environmental degradation, and global economic instability.

Closely linked to food security is the concept of food sovereignty, which emerged as a social and political movement advocating the rights of communities, farmers, and nations to control their own food systems, as stated by [5]. Introduced by La Via Campesina in the 1990s, food sovereignty emphasises local food production, equitable access to resources, sustainable agricultural practices, protection of indigenous knowledge, and democratic participation in food policy decisions [15].

Food sovereignty movements around the world have gained momentum in response to concerns regarding the industrialisation and globalisation of agriculture. Many developing countries have become increasingly dependent on imported food commodities, multinational agribusiness corporations, and international trade networks [14]. While globalisation has improved market access and increased food availability in many regions, it has also created vulnerabilities by concentrating production and distribution within complex supply chains that are susceptible to disruption [16]. Economic crises, geopolitical conflicts, trade restrictions, pandemics, and natural disasters can significantly affect the flow of food across borders, resulting in shortages, price volatility, and food insecurity, especially seen in rural areas [30].

The relationship between food security and food sovereignty is complementary rather than contradictory. Food sovereignty strengthens food security by promoting diversified agricultural systems, local food production, and community resilience [7]. Smallholder farmers play a critical role in maintaining biodiversity, preserving traditional crop varieties, and ensuring sustainable food production. By reducing dependence on external markets and imported inputs, local food systems can better withstand economic and environmental shocks [24].

Climate change represents one of the most significant threats to both food security and food sovereignty. Rising temperatures, erratic rainfall patterns, droughts, floods, and extreme weather events have adversely affected crop yields and livestock productivity worldwide [15]. Vulnerable populations, particularly in developing nations, face increased risks of hunger and malnutrition as agricultural systems struggle to adapt to changing environmental conditions. Food sovereignty approaches that promote agroecological farming, climate-resilient crop varieties, and sustainable resource management have been proposed as important strategies for enhancing resilience against climate-related challenges [16].

In addition to environmental threats, global food systems face increasing risks from biological hazards and intentional attacks. Bioterrorism and agroterrorism have emerged as serious concerns because food and agriculture represent critical infrastructures that support economic stability and public health [5]. Deliberate contamination of food products, introduction of plant pathogens, or outbreaks of livestock diseases can have devastating consequences for food production, trade, and consumer confidence [26]. Such incidents can undermine both food security and food sovereignty by disrupting local production systems and increasing dependence on external food supplies.

Recent global events have highlighted the fragility of food systems. The COVID-19 pandemic disrupted agricultural labour availability, transportation networks, food processing operations, and international trade. Lockdowns and border restrictions affected the movement of agricultural commodities, exposing weaknesses in global supply chains [22]. These disruptions reinforced the importance of building resilient food systems capable of maintaining food availability and accessibility during crises. Countries with stronger domestic production systems and diversified supply chains were generally better positioned to withstand the impacts of the pandemic [23].

Technological innovation is increasingly recognised as a key component in strengthening food security and food sovereignty [11]. Advances in artificial intelligence (AI), remote sensing, precision agriculture, Internet of Things (IoT) technologies, and blockchain-based traceability systems offer new opportunities to improve agricultural productivity, monitor food quality, and enhance supply chain transparency [13]. These technologies can support evidence-based decision-making, reduce production risks, and improve the efficiency of food distribution systems. At the same time, equitable access to these technologies is essential to ensure that smallholder farmers and developing countries are not left behind in the digital transformation of agriculture [20].

Ultimately, the need of the study is to achieve sustainable food security, which requires a balanced approach that combines the principles of food sovereignty with modern technological innovations and effective governance mechanisms. Strengthening local food systems, protecting agricultural resources, supporting smallholder farmers, and enhancing resilience against biological, environmental, and economic threats are critical for ensuring long-term food sustainability [24]. As food systems continue to evolve in an increasingly interconnected world, policies that integrate food security, food sovereignty, and technological advancement will play a crucial role in safeguarding the future of global agriculture and nutrition [27].

3. RESEARCH METHODOLOGY

The manuscript was developed using reviews based on institutional reports and secondary literature cited in the reference list. The review mainly synthesises evidence that is related to keywords such as “bioterrorism and agroterrorism”, “food sovereignty”, “food security”, “food defence assessments”, “use of AI, blockchain, IoT and robotics”, “food system disruption”, “COVID-19-related food sovereignty” and “future of food regulations”. The evidence is sourced from manuscripts that highlight peer-reviewed literature and reports from International Organisations such as WHO, WTO, FAO, IFPRI, World Bank, UNEP, OECD, the United Nations, IFAD and CDC.

The synthesis of the Literature is thematic rather than statistical, and evidence is organised around 4 analytical regions: (I) threats and vulnerability to global food systems, (II) technology-based food defence and regulation, (III) implementation obstacles and requirements of governance and (IV) Lessons learned for future policy directions and Covid-19. No human or animal subjects were used in the research for experimental intervention, and no data analysis was conducted; therefore, the research does not require institutional ethical approval.

4. RESEARCH AND VALIDATION

4.1 Bioterrorism: A Threat to Global Food Systems

Bioterrorism represents one of the most serious emerging threats to global food security, public health, and economic stability, as stated by [22]. It involves the intentional release or introduction of biological agents such as bacteria, viruses, fungi, toxins, or other harmful microorganisms into food production systems, agricultural environments, livestock populations, or food supply chains with the objective of causing widespread disruption, illness, fear, and economic damage. Bioterrorism is different from conventional security threats in that it can remain undetected for extended periods, allowing contamination to spread rapidly through interconnected food systems before effective countermeasures can be implemented [23].

The globalisation of food production and trade has significantly increased the vulnerability of food systems to biological attacks [10]. The successful attack on a critical component of the food supply chain can result in substantial economic losses, trade restrictions, reduced consumer confidence, and severe public health consequences [6]. Consequently, food defence has become a critical aspect of national security and agricultural policy in many countries.

Agricultural bioterrorism, often referred to as agroterrorism, specifically targets crops, livestock, agricultural infrastructure, or food-processing facilities. Attacks on agricultural systems can be particularly attractive to terrorists because they often require relatively low-cost biological agents while producing significant economic and psychological impacts. For example, the

deliberate introduction of highly contagious animal diseases such as Foot-and-Mouth Disease (FMD), Avian Influenza, African Swine Fever, or crop pathogens can result in widespread destruction of agricultural commodities, export bans, and long-term recovery costs [22]. Such incidents may not only threaten food availability but also undermine food sovereignty by increasing dependence on imported food products.

To address these threats, governments and regulatory agencies have developed various food defence and vulnerability assessment tools. Among these, the CARVER+Shock methodology has emerged as one of the most widely recognised frameworks for identifying vulnerabilities within food systems. The CARVER+Shock model evaluates potential targets based on seven factors: Criticality, Accessibility, Recuperability, Vulnerability, Effect, Recognizability, and Shock [23]. This systematic approach enables authorities to prioritise security measures and allocate resources toward protecting high-risk components of food supply chains. The model has been extensively applied in the United States and several other countries to strengthen food defence strategies and improve preparedness against intentional contamination events.

International trade agreements also play a crucial role in shaping food security and food defence. The World Trade Organisation (WTO) has established agreements such as the Sanitary and Phytosanitary (SPS) Agreement and the Technical Barriers to Trade (TBT) Agreement to facilitate safe and fair trade while protecting human, animal, and plant health [6]. The COVID-19 pandemic demonstrated how rapidly global crises can strain regulatory systems, delay inspections, restrict trade, and expose weaknesses in international food governance mechanisms.

The COVID-19 pandemic provided valuable lessons regarding the resilience of food systems under conditions of extreme stress. Lockdowns, labour shortages, transportation restrictions, and border closures disrupted agricultural production and food distribution networks across the world [4]. Food processing facilities experienced operational challenges, while export restrictions and supply chain interruptions affected the availability of essential commodities [12]. These disruptions highlighted the need for more adaptive, technology-driven food defence systems capable of providing real-time monitoring, rapid risk assessment, and coordinated international responses.

Emerging technologies such as Artificial Intelligence (AI), machine learning, remote sensing, blockchain, and Internet of Things (IoT) platforms are increasingly being explored as tools for strengthening food defence and mitigating bioterrorism risks [20]. AI-based systems can analyse large volumes of data to identify unusual patterns, predict contamination events, and generate early warnings before threats escalate into large-scale crises [21].



Figure 2: carver+shock risk assessment model for food systems

4.2 Artificial Intelligence and Robotics in Food Regulation

Artificial Intelligence (AI) and robotics are revolutionising food regulatory systems by enhancing the efficiency, accuracy, transparency, and responsiveness of food safety monitoring and management. Traditional food regulatory frameworks often rely on manual inspections, laboratory testing, and reactive interventions that may not adequately address the increasing complexity of modern food supply chains [11]. One of the most significant applications of AI in food regulation is predictive analytics. Machine learning algorithms can process vast amounts of agricultural, environmental, epidemiological, and market

data to identify patterns associated with disease outbreaks, pest infestations, food adulteration, and contamination risks [3]. AI systems can forecast potential threats before they occur, allowing regulatory authorities and food producers to implement preventive measures [20].

AI-driven sensor technologies have also improved food quality assurance and safety monitoring. Advanced biosensors, hyperspectral imaging systems, and computer vision technologies can detect microbial contamination, chemical residues, adulterants, and quality defects with high precision [21]. Hyperspectral imaging combines spectroscopy and digital imaging to identify invisible changes in food composition, enabling rapid, non-destructive assessment of food quality. Such technologies are particularly useful in detecting contaminants in fruits, vegetables, dairy products, meat, and processed foods.

Robotics is playing an increasingly important role throughout the food production and processing chain. Automated robotic systems are capable of performing repetitive inspection, sorting, packaging, and quality control tasks with greater consistency and efficiency than manual labour. Robotics reduces the risk of human error and minimises direct human contact with food products, thereby improving hygiene and food safety standards [19].

The emergence of blockchain technology has further strengthened food regulatory systems by improving transparency and traceability. Blockchain creates a decentralised and tamper-resistant digital ledger that records every transaction and movement within the food supply chain. When integrated with AI and IoT devices, blockchain enables end-to-end tracking of food products from farm to consumer [21]. This transparency facilitates rapid identification of contamination sources, supports product recalls, and enhances consumer confidence.

The Internet of Things (IoT) has become a critical component of AI-enabled food regulation. IoT devices such as smart sensors, RFID tags, GPS trackers, and environmental monitoring systems continuously collect data related to temperature, humidity, storage conditions, transportation routes, and product handling [18]. AI algorithms analyse this information to identify deviations from safety standards and generate real-time alerts.

Despite their significant benefits, the adoption of AI and robotics in food regulatory systems faces several challenges. High implementation costs, limited digital infrastructure, data quality issues, cybersecurity risks, and concerns regarding data privacy can hinder widespread adoption, particularly in developing countries [11]. AI algorithms may produce inaccurate predictions if trained on incomplete or biased datasets [12]. Regulatory agencies must therefore establish clear standards for data governance, transparency, validation, and accountability to ensure reliable decision-making.

The future of food regulation is expected to be increasingly driven by intelligent technologies that integrate AI, robotics, blockchain, IoT, and advanced analytics into comprehensive food governance frameworks. Such systems will support real-time monitoring, automated compliance verification, rapid contamination detection, and predictive risk management [13]. As global food systems continue to expand and become more interconnected, the adoption of AI-driven regulatory tools will be essential for ensuring food safety, protecting public health, enhancing supply chain resilience, and safeguarding food sovereignty.

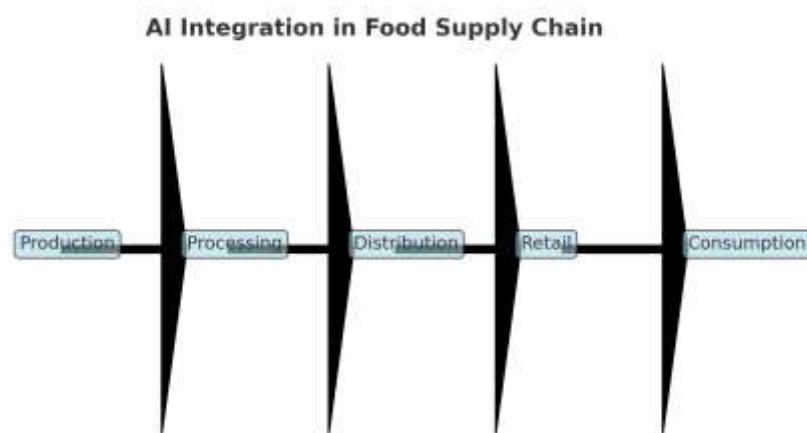


Figure 3: ai integration in the food supply chain

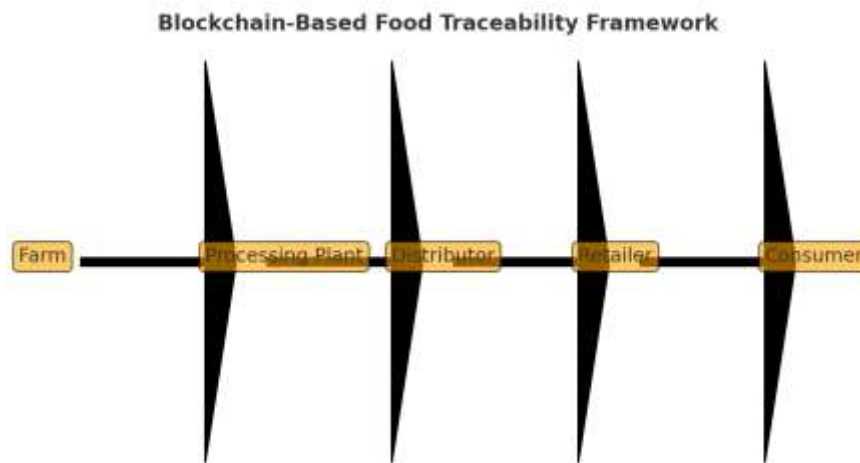


Figure 4: blockchain-based food traceability framework

4.3 Challenges in Implementing AI-based Food Regulatory Systems

Artificial Intelligence (AI), robotics, blockchain, and digital technologies offer significant opportunities to enhance food safety, food defence, and regulatory efficiency, their large-scale implementation faces several technical, economic, ethical, and governance-related challenges [13]. These barriers are particularly pronounced in developing countries. Addressing these challenges is essential to ensure that AI-driven food regulatory frameworks are effective, inclusive, and sustainable [14].

AI implementation is high cost associated with technological infrastructure. AI-powered food surveillance systems require substantial investments in sensors, data collection platforms, cloud computing resources, advanced analytical tools, robotics, and skilled personnel [13]. Many low- and middle-income countries struggle to allocate sufficient financial resources for digital transformation, particularly when faced with competing priorities such as healthcare, education, and agricultural development, and this inequality creates lesser regulatory preparedness [20].

Data availability and quality represent another major challenge. AI systems depend heavily on large volumes of accurate, reliable, and standardised data for training and decision-making [11]. In many regions, food safety records, agricultural databases, and supply chain information are incomplete, inconsistent, or fragmented across different institutions [18]. Poor-quality and unstandardised data can significantly reduce the accuracy of predictive models and increase the likelihood of incorrect risk assessments.

Data privacy and cybersecurity concerns have become increasingly important as food regulatory systems adopt digital technologies [12]. AI-driven platforms often collect and process large amounts of sensitive information related to agricultural production, supply chains, business operations, and consumer behaviour. Unauthorised access, data breaches, cyberattacks, or manipulation of digital records could compromise food safety systems and undermine public trust [13].

Ethical concerns also play a significant role in the implementation of AI-based regulatory systems. The use of automated decision-making tools raises questions regarding transparency, accountability, fairness, and human oversight [13]. Many AI algorithms operate as “black-box” systems, making it difficult for regulators and stakeholders to understand how decisions are reached due to a lack of transparency [28]. Ethical governance frameworks are therefore necessary to ensure the operability of AI.

Algorithmic bias is a significant concern. AI models learn from historical datasets, and if these datasets contain biases, inaccuracies, or incomplete information, the resulting predictions may be unreliable [12]. In food safety applications, biased algorithms may fail to identify certain contamination risks, disproportionately affect specific regions or producers, or generate inaccurate risk classifications. False positives and false negatives may allow contaminated food products to reach consumers [13].

Public acceptance and trust are another challenge [11]. Consumers may be sceptical about the increasing use of AI and automation in food production and regulation, particularly if they perceive these technologies as replacing human judgment

[12]. Building trust requires transparent communication regarding the benefits, limitations, and safeguards associated with AI systems. Public engagement and stakeholder participation are essential [25].

Addressing these challenges requires coordinated governance, international collaboration, and sustained investment in digital infrastructure [13]. Governments, regulatory agencies, research institutions, and private-sector organisations must work together to mitigate these issues. International organisations such as the FAO, WHO, WTO, and Codex Alimentarius Commission can play a crucial role in facilitating and establishing globally accepted standards for AI-driven food regulation [27]

4.4 Case Studies and Lessons from COVID-19

The COVID-19 pandemic represents one of the most significant global disruptions to food systems in recent history [2]. The pandemic was primarily a public health emergency; its consequences were beyond healthcare systems, affecting agricultural production, food processing, transportation networks, and international trade. The crisis exposed vulnerabilities within global food supply chains and demonstrated the urgent need for more resilient, technology-enabled food governance systems [4].

At the onset of the pandemic, governments worldwide implemented lockdowns, travel restrictions, border controls, and social distancing measures to limit the spread of the virus. While these interventions were necessary from a public health perspective, they significantly disrupted food production and distribution systems [2]. Agricultural sectors experienced labour shortages due to movement restrictions, particularly in labor-intensive industries such as fruit, vegetable, dairy, and livestock production [7].

Food processing and packaging facilities also faced operational challenges. Several processing plants were temporarily closed due to COVID-19 outbreaks among workers, leading to reduced production capacity and interruptions in food supply. Meat processing facilities in various countries experienced significant disruptions, highlighting the vulnerability of centralised food production systems. These disruptions contributed to temporary shortages, increased food prices, and growing concerns regarding food availability in both developed and developing nations. [2, 7].

Many countries imposed export controls on essential food commodities to protect domestic supplies, further increasing uncertainty in global markets. Such measures affected the movement of cereals, pulses, edible oils, and other staple foods, particularly in regions highly dependent on imports [6]. The pandemic demonstrated how quickly disruptions in one part of the world can affect food availability and affordability elsewhere due to the interconnected nature of global supply chains.

The implementation of the World Trade Organization's Sanitary and Phytosanitary (SPS) Agreement and Technical Barriers to Trade (TBT) Agreement faced unprecedented challenges during the pandemic [6]. Regulatory agencies responsible for inspections, certification, laboratory testing, and border controls encountered significant operational difficulties due to staffing shortages, travel restrictions, and reduced field activities [9]. Delays in inspections and certification processes affected international trade flows and impacted the agricultural supply chain [12].

One important lesson from the pandemic is maintaining food system functionality. Countries with established digital infrastructure and AI-supported regulatory systems demonstrated adaptability [11]. Several EU member states accelerated the use of electronic certification, remote inspections, digital traceability systems, and automated risk assessment tools to maintain regulatory oversight despite mobility restrictions [13, 29]. Artificial Intelligence played an important role in supporting food system resilience. AI-based analytics helped governments and businesses monitor supply chain disruptions, forecast demand fluctuations, and optimise logistics [19]. ML algorithms analysed large datasets related to production, transportation, weather conditions, and market trends to support evidence-based decision-making with the development of predictive models [21].

Digital traceability systems proved valuable during the pandemic, which facilitated real-time tracking of food products throughout supply chains [13]. These technologies improved transparency, reduced information asymmetry, and enhanced the ability of regulatory agencies to identify and address bottlenecks [20]. In situations where physical inspections were limited, digital records provided alternative mechanisms for verifying product safety and regulatory compliance.

Developed nations leveraged advanced digital tools and AI-based systems to support food governance, but numerous developing countries struggled with limited technological infrastructure, insufficient internet connectivity, inadequate data management systems, and shortages of skilled personnel [5]. The pandemic emphasised the importance of investing in digital capacity building and technological modernisation to strengthen food system resilience globally [14]. There is a requirement to develop localised food systems. Countries that relied heavily on imported food commodities experienced greater vulnerability

to supply chain disruptions and trade restrictions [5]. Regions with stronger domestic production capacities and diversified supply networks often demonstrated greater resilience.

The pandemic lessons help in creating integrated crisis management frameworks that combine food security, public health, trade policy, and technological innovation [11]. Future food regulatory systems must be capable of responding rapidly to biological threats, whether naturally occurring or intentional, needs to AI-driven surveillance systems and real-time data sharing platforms [12].

COVID-19 pandemic served as a global stress test for food systems and regulatory institutions. It exposed critical vulnerabilities in supply chains, highlighted limitations in traditional inspection and certification systems, and demonstrated the strategic importance of digital technologies in maintaining food security [2]. The experiences gained during the pandemic provide valuable insights for developing more resilient, adaptive, and technology-driven food governance frameworks. Integrating Artificial Intelligence, blockchain, IoT, and advanced analytics into food regulatory systems will be essential for enhancing preparedness [7].

5. DISCUSSION

The future of global food security and food regulation will increasingly depend on the successful integration of Artificial Intelligence (AI), robotics, blockchain, Internet of Things (IoT), big data analytics, and advanced surveillance technologies into comprehensive regulatory frameworks [11, 13]. As food supply chains become more complex and interconnected, traditional food safety and defence systems will no longer be sufficient to address emerging challenges such as bioterrorism, climate change, pandemics, cyber threats, and global trade disruptions.

One of the most promising future developments is the establishment of international AI-based early warning systems for food safety and food defence [12, 18]. Machine learning algorithms could continuously analyse large datasets to detect unusual patterns associated with contamination events, pest outbreaks, crop diseases, food fraud, and intentional attacks. Early detection would enable authorities to implement preventive measures before threats escalate into large-scale public health emergencies or economic crises.

Integrating AI with CARVER+Shock would allow continuous monitoring of critical food infrastructure and dynamic risk scoring based on real-time conditions [20, 23]. Predictive models could identify vulnerable nodes within supply chains, forecast potential attack scenarios, and support more effective allocation of resources for food defense and emergency preparedness.

When combined with IoT-enabled sensors, blockchain platforms can create fully transparent supply chains that allow regulators, producers, retailers, and consumers to access accurate information regarding product origin, storage conditions, quality standards, and compliance records [19]. Enhanced traceability will facilitate rapid product recalls, improve accountability, reduce food fraud, and strengthen consumer confidence [17].

AI algorithms can analyse these data streams to identify anomalies and generate automated alerts when safety thresholds are exceeded. Such capabilities will support preventive interventions, minimise food losses, and improve overall supply chain efficiency. [21]

Governments, academic institutions, technology companies, food industries, and international organizations should collaborate to develop affordable and scalable digital solutions that can be adapted to diverse agricultural and regulatory environments [11, 13]. Public-private cooperation can support research and development activities, infrastructure investments, workforce training programs, and pilot projects that demonstrate the effectiveness of AI-based food governance systems [8].

The successful implementation of AI-driven regulatory frameworks requires professionals with expertise in food science, data analytics, artificial intelligence, cybersecurity, risk assessment, and regulatory policy [11]. Universities and research institutions should develop interdisciplinary training programs that prepare future professionals to manage increasingly complex digital food systems [12, 25]. Continuous professional development and international knowledge-sharing initiatives will further strengthen institutional capabilities and improve regulatory effectiveness.

Currently, considerable variation exists among countries regarding food safety requirements, inspection procedures, data management practices, and technology adoption. International organisations such as the Food and Agriculture Organisation (FAO), World Health Organisation (WHO), World Trade Organisation (WTO), Codex Alimentarius Commission, and

International Plant Protection Convention (IPPC) should work together to establish globally accepted standards for AI applications, blockchain traceability, cybersecurity protocols, and digital food safety monitoring. Harmonised frameworks will facilitate cross-border cooperation, improve data sharing, and enhance the efficiency of international food trade. [12, 13]

Ethical governance must remain a central consideration as AI becomes increasingly integrated into food regulatory systems. Policymakers should establish transparent guidelines for data privacy, algorithm accountability, explainability, fairness, and human oversight. Mechanisms for auditing AI systems should be developed to minimise algorithmic bias, prevent discriminatory outcomes, and ensure public trust [14, 15]. Ethical frameworks should balance innovation with social responsibility to ensure that technological advancements benefit all stakeholders, including smallholder farmers, consumers, and vulnerable populations.

Future food regulatory systems should also embrace resilience-oriented approaches that integrate food security, food sovereignty, sustainability, and technological innovation. Investments in climate-resilient agriculture, digital infrastructure, diversified supply chains, and local food production systems can strengthen the capacity of communities and nations to withstand future disruptions [11, 13]. Combining technological solutions with sustainable agricultural practices will create more adaptive and robust food systems capable of addressing both natural and intentional threats.

In the coming decades, AI-powered digital ecosystems are expected to transform food governance from a predominantly reactive model into a predictive and preventive system[1]. Real-time surveillance, intelligent risk assessment, automated compliance verification, digital traceability, and coordinated international response mechanisms will become essential components of global food regulation [11, 12]. These innovations have the potential to significantly reduce foodborne disease outbreaks, improve regulatory efficiency, enhance food defense capabilities, and strengthen public confidence in food systems.

Ultimately, global collaboration will be indispensable for safeguarding food sovereignty while enabling safe, transparent, and efficient international trade. The successful implementation of AI-based regulatory frameworks will require collective action, sustained investment, technological inclusiveness, and strong institutional commitment [5, 14]. By embracing innovation while addressing ethical, economic, and governance challenges, the international community can build resilient food systems capable of ensuring food security, protecting public health, and supporting sustainable development in an increasingly uncertain world.

6. CONCLUSION

Global food security and food sovereignty are facing unprecedented challenges in the twenty-first century due to the combined impacts of climate change, population growth, geopolitical conflicts, pandemics, environmental degradation, and emerging biological threats. The increasing globalization brought food vulnerabilities such as bioterrorism and agroterrorism, which represent serious concerns because deliberate contamination of food products, crops, or livestock can disrupt food supplies, damage economies, undermine consumer confidence, and threaten public health on a large scale [5, 15, 16]. The experiences of the COVID-19 pandemic further demonstrated how rapidly global crises can destabilise food systems, revealing weaknesses in existing regulatory frameworks and highlighting the need for more resilient and adaptive approaches to food governance.

This review has emphasised that food sovereignty and food security are closely interconnected objectives that require both local resilience and global cooperation. While food sovereignty movements advocate greater local control over food production and distribution systems, the realities of modern food trade necessitate robust international regulatory mechanisms capable of preventing and responding to biological, environmental, and technological risks. Traditional food defence approaches, including vulnerability assessment frameworks such as CARVER+Shock, have contributed significantly to risk identification and preparedness. However, the growing complexity of global supply chains demands more sophisticated tools that can provide real-time surveillance, predictive risk assessment, and rapid response capabilities [22, 23].

AI-driven solutions offer unprecedented opportunities to improve contamination detection, disease surveillance, traceability, supply chain monitoring, and regulatory decision-making. Predictive analytics can identify emerging threats before they become large-scale crises, while blockchain-enabled traceability systems enhance transparency and accountability throughout the food value chain [2, 7]. Robotics and automation further contribute to food safety by improving inspection accuracy, reducing human error, and increasing operational efficiency.

Despite these advantages, several challenges continue to hinder the widespread implementation of AI-based food regulatory systems. High infrastructure costs, technological inequalities, limited digital capacity, cybersecurity threats, data privacy

concerns, algorithmic bias, and the absence of harmonised international standards remain major obstacles, particularly in developing countries [5, 14]. Addressing these barriers will require sustained investment in digital infrastructure, capacity building, regulatory modernisation, and international cooperation. Ethical governance frameworks must also be established to ensure transparency, accountability, fairness, and public trust in AI-driven decision-making processes.

The future of food regulation will increasingly depend on integrated digital ecosystems that combine AI, robotics, blockchain, IoT, and advanced surveillance technologies into comprehensive food governance frameworks. International collaboration among governments, regulatory agencies, research institutions, industry stakeholders, and global organisations will be essential for developing standardised approaches to food defence, food safety, and risk management. Strengthening public-private partnerships, enhancing knowledge-sharing mechanisms, and promoting equitable access to technological innovations will further support the development of resilient food systems capable of withstanding future disruptions [6, 10].

In conclusion, the integration of AI into food regulatory systems is no longer merely an option but a strategic necessity for ensuring global food security, food sovereignty, and public health protection. As biological threats, climate-related challenges, and global uncertainties continue to evolve, technology-driven governance systems will play a crucial role in safeguarding food supplies and maintaining consumer confidence. The successful implementation of AI-enabled food defence and regulatory frameworks will require a balanced approach that combines technological innovation with ethical responsibility, social inclusiveness, and effective governance. By embracing these principles, the global community can build more resilient, transparent, and sustainable food systems capable of meeting the challenges of the future while ensuring safe, nutritious, and accessible food for all [11, 13].

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9. DATA AVAILABILITY

New data were analysed or created for this particular study. Latest sharing is not applicable for this manuscript.

10. CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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